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New instrumentation has been designed, developed and deployed for characterizing ice and water droplets in clouds in the atmosphere by in situ aircraft measurement. The principle of operation depends on capture of the particles on a forward facing probe and their processing through evaporation and/or melting to give particle mass and density. Data is both video recorded and also obtained as permanent record as a plastic cast. New analysis tools have also been developed for analysis of the results, displaying particle forms, concentration and spatial distribution in high resolution. Test results have been obtained in hurricane outflow, in arctic clouds and in aircraft contrails. Application lies in determining the optical properties of such clouds from the viewpoint of their influence on laser propagation and transfer of atmospheric radiation; it also lies in characterizing clouds in terms of their potential for enhanced aircraft icing when specific spatial distributions of ice particles and supercooled cloud exist.

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Executive Summary

In order to address Air Force requirements for high level aircraft and satellite remote sensing, the effectiveness of directed beam energy systems and aircraft flight safety under combined supercooled water and ice cloud conditions, instrumentation has been designed and built to characterize the properties of level clouds at tmperatures below 0C. A large sample volume cloudscope, some 10 liters per second, has been designed and built; a small sample cloudscope, sample volume 50 cm^3 per second and a replicator sample volume 1 liter per second has been flown in parallel to provide comparative data. The instruments rely on collection of particles carried by aircraft through the region of interest. Analysis of airflow around cloudscope and replicator gives collection efficiency for particles and only falls to low values for low density (0.2) and smaller diameter (< 2μm) ice particles. Collected particles are either processed in situ (evaporated, melted) and videotaped or replicated for subsequent analysis. Estimates are also made of the effect of impaction of the collected particles, a property having importance in aircraft ice accretion. Direct measurements give particle concentration, size and shape. Measurement of the particle evaporation rate gives a measure of the particle density, instantaneously related to its radius. Derived products include mass mixing ratio, particle area, and particle mass flux and accreted ice erosion by ice particle impact.

Instruments have been test flown in several projects and the data analyzed to demonstrate its utility and limitations. Software has been modified to provide semi-automated analysis of flight data and to provide a variety of derived products. Important results suggest the universal occurrence of ultragiant hygroscopic nuclei in highly variable concentrations and the presence of small ice particles in high concentrations in some contrails. Results have provided the basis for a MS thesis in Atmospheric Sciences in the University of Nevada, Reno (Meyers 1999); have been presented in two conferences (Meyers et al 1999; Hallett et al 1999) and submitted for publication. (Meyers & Hallett 2000; Hallett et al 2000).

Technical Description.

1.Introduction.

High level ice clouds are of importance to Air Force operations from several perspectives. First, such clouds impede surface observation by satellite and high flying aircraft at solar, thermal and to a lesser extent, at microwave wavelengths. Natural high level clouds can be forecast with some generality, but detailed characteristics - such as optical depth - depend critically on microphysical and microdynamical process which are not well understood and cannot be well predicted. Natural clouds are subject to significant modification be aircraft operations, first by adding nuclei from engine combustion to the atmosphere which can make natural clouds optically thicker, and also by direct formation of contrails, which evaporate to varying lengths depending on ambient conditions. Sometimes contrails grow in a cloud free ice supersaturated /water undersaturated atmosphere to cover the whole sky.

A further problem which arises in high level clouds lies in the propagation of electromagnetic radiation at a variety of wavelengths. The. phenomenum of ducting has been well known for many years and is difficult to predict and use because of the complexity and unpredictability of the detail of the structure or moisture and thermal inversions. Particles give rise to other complications in association with inversion layers because they may be asymmetric and sometimes fall with maximum area horizontal. Particles may also undergo oscillations of varying frequency as they fall resulting either from eddy shedding or, for small particles, from Brownian motion. These phenomena may be complicated in the presence of electric fields which may orient such particles in directions other than horizontal. These considerations are not only relevent to communication - and sensing as radar detection - but also for propagation of directed energy as laser beams which could be redirected or even sent along a reverse path. Occasionally supercooled water cloud is also present at low temperatures (<-30C), giving a possible icing hazard when it would not normally be expected. Such an effect may be enhanced in the presence of supercooled water and ice cloud in close proximity.

All of these topics require characterization of ice particles at various stages of growth or evaporation as a prelude to prediction. This issue has been addressed in the work herein reported and new instrumentation and analysis techniques have been developed and used under a variety of atmospheric conditions to examine the nature of ice particles.

2. Instrumentation

The formvar replicator (Hallett,1976) and the cloudscope (Arnott and Hallett,1995; Hallett et al 1998) are instruments which rely on impaction from an aircraft in motion for their operation. Hence observations of particle concentration need correction for collection efficiency in the ambient air flow; both instruments also need to take into consideration the impact and possible breakup of the particle on collection. The replicator works by making casts of the collected particles, following evaporation of a plastic in solution. The casts are examined in the laboratory after collection by optical and electron microscopy. The cloudscope works as particles are impacted on a forward facing optical flat and video recorded. Particles melt and evaporate as they are collected on a heated surface. The density of the particle can be deduced from the rate of evaporation or melting and evaporation, and is inversely related to the slope of the particle area - time graph. A comparison of the sample volume rate of these instruments with other instrumentation is shown in Figure 1.

3. Accomplishments:

A large format cloudscope has been designed and built. Figure 2 shows a comparison with the earlier, small sample volume, instrument. Both instruments are capable of insertion into a standard aircraft instrument pod, and way be easily interchanged during field projects. Particles are impacted on a large sapphire window (2.5 cm diameter) with heating capability by current flow through a rear surface conducting thin film. Two busses provide current in/out flow. There is temperature measurement and control of the window extending above and below 0C.

The instrument was test flown in Arctic clouds in SHEBA (April 1998) in the NCAR C130. A modified version was test flown in the CAMEX mission on the NASA DC-8 (September 1998) to sample the cirrus of hurricane outflow in the 1998 season. As a result of these tests, The design has been modified to remove an image vibration problem which seriously impaired the digital analysis techniques used for sequential frame analysis.

A major modification was undertaken in 1999 to provide side viewing of impacted ice particles on accretion. This was undertaken by a second video camera mounted to one side of the first, viewing the impaction from the side via a prism optical system (Figure 3). The camera operates at a higher speed of 180 frames per second and detects particle impaction, bounce and particle erosion. The instrument was test flown on

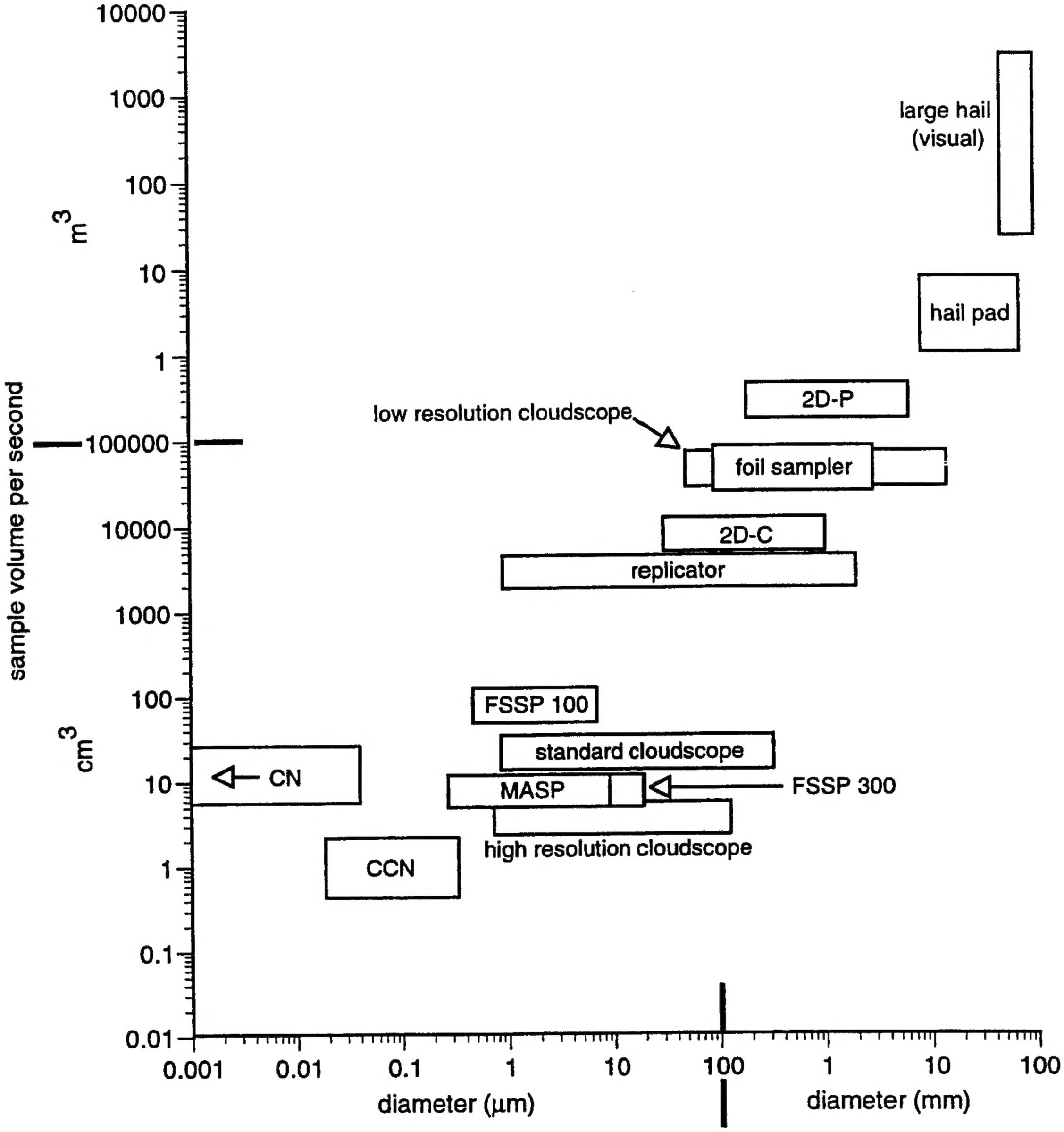
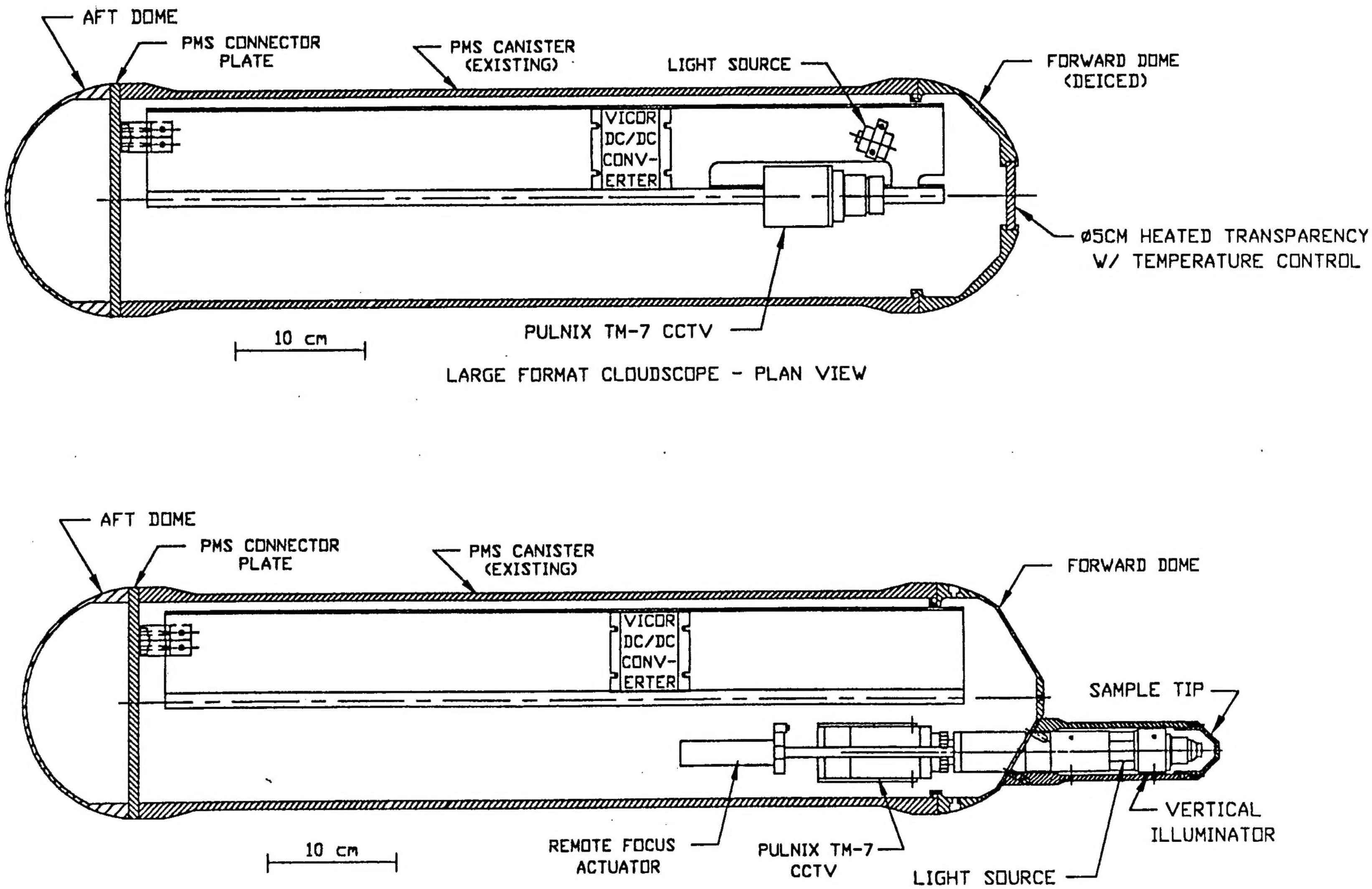


Figure 1 The response of instrument design to the dynamic range of particles for aircraft velocities from 90 m s^{-1} to 230 m s^{-1}. CN, condensation nuclei aerosol counter; CCN, cloud condensation nuclei aerosol counter (Hudson, 1989); MASP, multiangle aerosol spectrometer probe (Baumgardner et al., 1995); FSSP 100, fast scattering spectrometer probe (Baumgardner et al., 1992); FSSP 300, fast scattering spectrometer probe (Baumgardner et al., 1992); 2D-C, two dimensional particle imaging spectrometer - cloud (Heymsfield and Parrish, 1978); 2D-P, two dimensional particle imaging spectrometer - precipitation (Gordon and Marwitz, 1984); replicator (Hallett, 1976); cloudscope (Arnott et al., 1995); foil sampler (Brown, 1958; Knight et al., 1977).

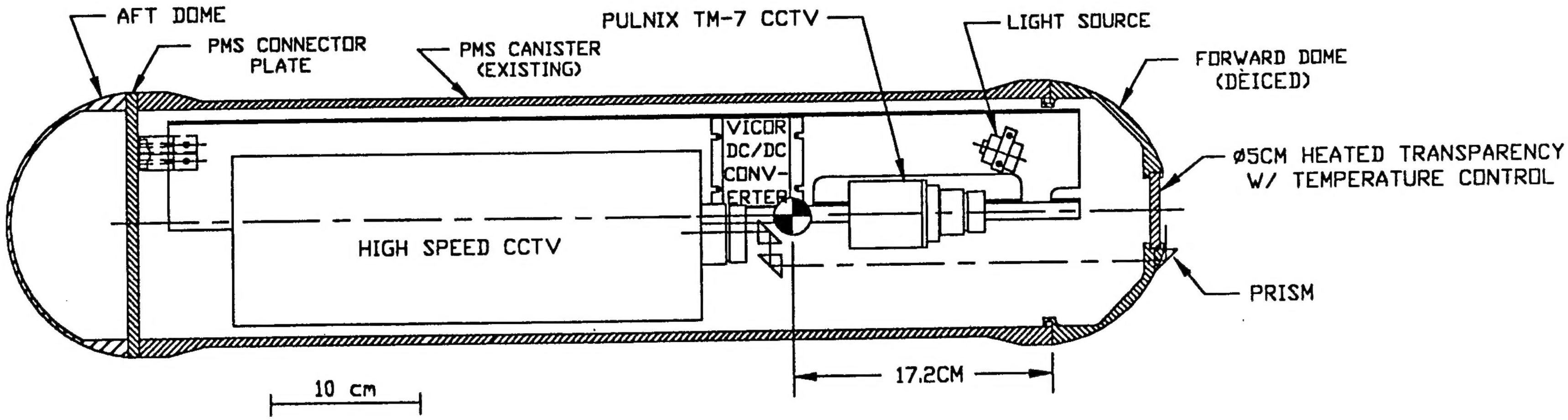


STANDARD RESOLUTION CLOUDSCOPE - PLAN VIEW

Figure 2.

Top: Large Format Cloudscope with 2.5 cm forward facing sapphire window. Sample volume 5 - 10 liters per second.

Bottom: Small Format Cloudscope with 0.5 X 0.5 sapphire window field of view and sample volume 25 - 50 cm^3 s^{-1}. Both instruments are readily exchange in a standard aircraft mounting pod.



LARGE FORMAT CLOUDSCOPE WITH HIGH
SPEED SIDE LOOKING CCTV - PLAN VIEW
WGT LESS CANISTER AND CONNECTOR PLATE = 3.6KG
CG EXCLUDES CANISTER AND CONNECTOR PLATE

Figure 3.

Large Format Cloudscope modified for simultaneous sideways and forward viewing of accreting ice. The sideways viewing camera was operated at 180 frames per second and the forward facing camera at standard 30 frames per second.

the Canadian Convair during the AIRS icing project With FAA support) in Dec 1999 and February 2000. Initial analysis of the data showed that ice accretion at the stagnation point was limited be erosion of existing accreted ice particles by incoming ice particles. A shock wave apparently moves sideways as a circular outflowing jet in the form of a disk and removed nearby ice particles. The results have implication that aircraft icing may be more serious following the apparently innocuous accretion of small amounts if ice at stagnation points under conditions such that accretion is followed by accretion of supercooled water droplets. Such droplets cement existing ice and prevent its erosion. Data from these tests are currently under more extensive analysis.

Analysis protocols have been developed for characterization of large and giant nuclei primarily observed during the arctic flights. Particles are observed during clear air flight legs and concentration determined along the legs. The hygroscopic nature of the particles is demonstrated by their observed dissolution as the aircraft enters air of higher relative humidity. The implication lies in the possible persistence of such particles (as having lower vapor pressure) and their role in forming an optically thin haze layer with corresponding effect on remotely retrieved data. In all cases the presence of giant/ultra (3 / >10μm) nuclei were sought, either in clear air or as the residues of evaporated particles. The cloudscope enables an estimate to be made of their hygrocopicity - that is their ability to take up water vapor as they dissolve at increasing relative humidity. Surprisingly, in all cases some regions were found where such particles were present in concentrations from a few to a few tenths per liter. This has possible cloud physics implications and also implications for interpretation of remotely sensed data, particularly as the particles change characteristics - shape, solute concentration and size with varying relative humidity. By contrast, extensive regions some hudreds of Km long were, on occasion, free of such particles.

Appendix A gives detailed analysis of aircraft data from the FIRE.ACE mission from Fairbanks on the NCAR C130 of the standard resolution cloudscope.

Following establishment of analysis protocols for formvar data collected in aircraft contrails during the NASA SUCCESS mission, particle images, using both optical microscopy and scanning electron microscopy techniques have been obtained. Specifically, image data from a

penetration of a Boeing 757 contrail on May 4 1996 has been examined in detail. Examination of 10 second periods (some 2 km length) has shown the presence of small ice particles in concentration mean 0.1 cm^{-3} and maximum 1 cm^{-3}, of size some 10μm. These particles constituted the evaporating end of the contrail, some 5 km from the lead aircraft at a pressure altitude of 191 mb and a temperature of -62C. It was located in the region where the wing tip vortex was well developed and contained the visible contrail. Of major interest is the existence of trigonal (3 fold) symmetry ice particles particularly in regions of high ice concentration. Ice under most atmospheric conditions is of hexagonal (6 fold) symmetry, and the presence of 3 fold symmetry suggests the existence of stacking faults in the lattice, leading to local cubic structure, having 3 fold symmetry along the <111> axes. This is further suggested by the occasional presence of four fold symmetry particles. There is some suggestion that such effects may be associated with sulfur fuel impurities and more likely NO_X impurities from engine combustion.

Appendix B gives analysis of replicator data obtained in aircraft contrails on the NASA DC-8 in 1996.

Both appendix A and Appendix B are in process of formal publication.

4. Personnel:

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Engineering design & construction: Rick Purcell.

Electronic design & construction: Dan Wermers.

Detailed analysis of field data: Matthew Meyers.

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REFERENCES

Hallett, J. W. P. Arnott, R. Purcell and C. Schmidt, 1998: A Technique for characterizing Aerosol and Cloud Particles by Real Time Processing. *$PM_{2.5}$: A fine particle standard Proceedings of an International Specialty Conference,* Sponsored by *EPA Air & Waste Management Association,* Ed. By J. Chow and P. Koutrakis, 1998, *1,* 318-325.

Hallett, J., M. B. Meyers, M. P. Bailey, W. P. Arnott, B. Strauss and P. Wendling, 1999: The Morphology of Ice Crystals in Aircraft Contrails. *37th AIAA Conference on Aerospace Sciences Meeting and Exhibit,* 11-14 January, 1999, Reno, Nevada, 1-11.

Hallett, J., M. B. Meyers, M. P. Bailey, W. P. Arnott, B. Strauss and P. Wendling, 1999: The Morphology of Ice Crystals in Aircraft Contrails, (*Submitted for publication*).

Meyers, M. and J. Hallett, 2000: Aircraft measurements of giant and ultragiant hygroscopic nuclei in the Arctic, (*Submitted for publication*).

Meyers, M. J. Hallett, W. P. Arnott and J. Niehues-Brooks, 1999: Aircraft observations of giant nuclei in Arctic Regions. *AMS 5th Conference on Meteorology and Oceanography,* 11-14 January, 1999, Dallas, Texas, 188-191.

Meyers, M. J., *M.S.* 1999 Atmospheric Sciences, University of Nevada Reno. Thesis title: An Assessment of Aircraft Mounted Cloud Probes and their Measurement Characteristics in a Highly Variable Atmosphere. Supervisor: Dr. John Hallett.